An Advanced Computer Code for Single-Tuned Harmonic Filter Design

Kun-Ping Lin, Ming-Hoon Lin, and Tung-Ping Lin

Abstract— **The objective of this paper is to present a novel approach for limiting harmonic and improving reactive compensation for industrial power systems using single-tuned filters. The unique feature of the developed power distribution model is that it incorporates both the filter capacity and resonant point as design parameters. The model also considers the detuning effects due to temperature and frequency variations, as well as manufacturing tolerances. The proposed approach was implemented as a PC-based computer code, and it was integrated with a user-friendly graphical user interface. The developed analysis tool was employed to solve the harmonic problems of several industrial plants, and the results all showed great improvements after using this computer tool.**

Index Terms—**Filter, harmonic distortion, reactive compensation, total harmonic distortion.**

I. Introduction

The IEEE FILTER design practice for limiting harmonic and improving reactive compensation is depicted in Fig. 1 [1]. It requires that the capacitor voltage and capacity and the reactor impedance be predetermined. For engineers not knowing the appropriate initial estimates, the process has to be repeated until all the proper values are found. This trial-and-error approach can become very complex as more filters are included in the systems.

This paper presents a new approach that incorporates a novel power distribution model. The proposed distribution model eliminates the trial-and-error approach by including both the filter capacity and the resonant point as design parameters. The model also considers the detuning effects due to temperature and frequency variations, as well as manufacturing tolerances.

Computer programs have become useful design tools for electrical engineers in recent years for harmonic analysis and filter design [1], [2]. The proposed approach was implemented as a PC-based computer code. A user-friendly graphical user interface (GUI) was also integrated as a module to the developed computer code. The simulation process is fully automated, and the numerical turnaround is very fast. The analysis tool enables the detailed examination of each individual, as well as the total, harmonic distortions at the point of common coupling (PCC). The program also recommends filters with specifications appropriate to the system.

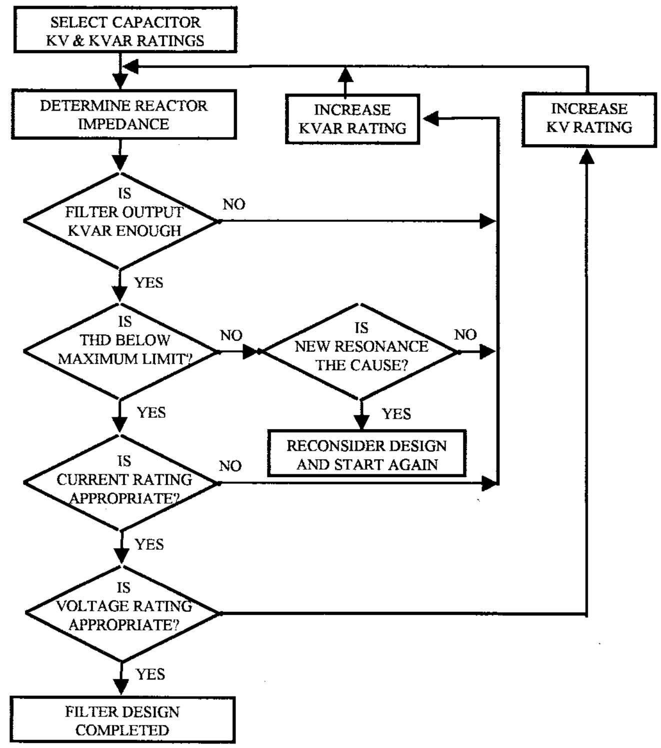

Fig. 1. Decision flow chart for single-tuned filter design.

This paper first presents the proposed new approach with the mathematical formulations of the novel power distribution model. The model implementation and solution procedure are then introduced. An industrial plant with existing harmonic problems was selected to demonstrate the capabilities of the developed analysis tool for limiting harmonics and improving reactive compensation using single-tuned filters.

II. Technical Approach

The new approach proposed here involves seven steps, as depicted in Fig. 2. *Step 1* is to perform the analysis and identify those unwanted harmonic distortions in the system. Based on the review, the necessary filters are included in the system. It is noted that the filter limiting the lowest order harmonic

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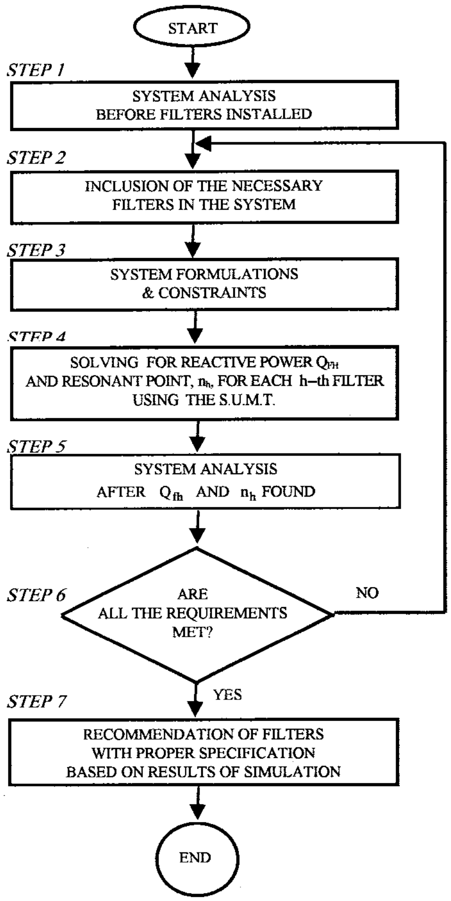

Fig. 2. Flow chart of the proposed approach.

distortion should be installed first, so the parallel resonance can be avoided.

Steps 3 and *4* are the core of the current approach. It is essentially a power distribution model that incorporates both the reactive power Q_{fh} and n_h resonant point as design parameters. First, the power system has to be formulated to take those added filters into account. To avoid any possible series resonance, the added filters have to be designed to function regardless of the variation of power sources and manufacturing tolerances. This means the derived system formulations are subject to certain design constraints, so that the filter detuning from its design value cannot devastate the entire system. To solve the system formulations with constraints, the so-called sequential unconstrained minimization technique (SUMT) [3] was employed. The solutions Q_{fh} and n_h are then obtained for each filter added in the system.

Step 5 is to perform system analysis after the designed Q_{fh} and n_h are found. Based on the results from *Step 5*, *Step 6* checks the system for the existence of any unwanted harmonic distortion and parallel resonance resulting from the filters added. If any requirement is not met, the process is started over, beginning from *Step 2*. If all the requirements are satisfied, the appropriate filter component ratings are then determined.

It is noted here that the approach outlined in Fig. 2 was implemented as a PC-based computer program, and the procedure is fully automated. No trial and error is needed.

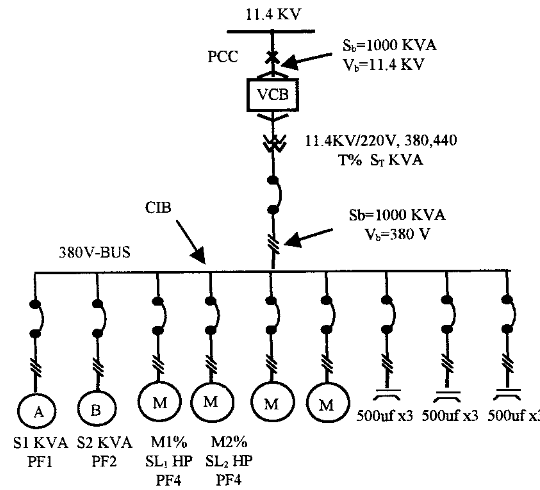

Fig. 3. A typical one-line diagram of an industrial plant.

III. System Formulations and Constraints

This section presents the mathematical formulations of the power distribution model as *Step 3* in Fig. 2. The formulations are first derived based on a simple example and then generalized for more complex systems. The filter design constraints to the system equations are also described.

A. System Equations

Fig. 3 shows a typical one-line diagram of an industrial plant that contains two harmonic loads A and B, and two ac loads $M1$ and $M2$. To focus on the power distribution model, we skip *Steps 1* and *2* by assuming the 5th-, 7th-, 11th-, and 13th-order harmonic distortions have been improved, and we decide to add four single-tuned filters and analyze the system at 60 Hz.

The impedance, PU, of the electric source, the transformer, the two ac loads, and the four added filters are expressed in the following:

$$X_s = \frac{1}{S} \quad \text{where } S = \frac{\text{SCC}}{S_b} \tag{1}$$

$$X_t = \frac{1}{S_t} \quad \text{where } S_t = \left(\frac{100}{T}\right) \times \left(\frac{S_T}{S_b}\right) \tag{2}$$

$$X_{M1} = \frac{1}{S_{M1}} \quad \text{where } S_{M1} = \left(\frac{100}{M1}\right) \times \left(\frac{SL_1}{S_b}\right) \tag{3}$$

$$X_{M2} = \frac{1}{S_{M2}} \quad \text{where } S_{M2} = \left(\frac{100}{M2}\right) \times \left(\frac{SL_2}{S_b}\right) \tag{4}$$

$$X_{C5} = \frac{1}{S_{F5}} \quad \text{where } S_{F5} = \left(\frac{Q_{F5}}{S_b}\right) \times \left(1 - \frac{1}{n_5^2}\right) \tag{5}$$

$$X_{C7} = \frac{1}{S_{F7}} \quad \text{where } S_{F7} = \left(\frac{Q_{F7}}{S_b}\right) \times \left(1 - \frac{1}{n_7^2}\right) \tag{6}$$

$$X_{C11} = \frac{1}{S_{F11}} \quad \text{where } S_{F11} = \left(\frac{Q_{F11}}{S_b}\right) \times \left(1 - \frac{1}{n_{11}^2}\right) \tag{7}$$

$$X_{C13} = \frac{1}{S_{F13}} \quad \text{where } S_{F13} = \left(\frac{Q_{F13}}{S_b}\right) \times \left(1 - \frac{1}{n_{13}^2}\right) \tag{8}$$

where

- SCC source short circuit capacity;
- S_b base capacity;
- Q_{Fh} filter capacity $h = 5$, 7, 11, and 13;
- n_{Fh} filter resonant point $h = 5$, 7, 11, and 13.

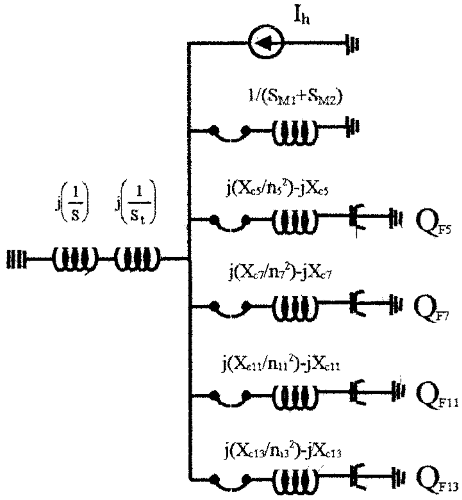

Fig. 4. The resultant equivalent circuit at 60 Hz.

The two harmonic loads A and B can be represented by a single harmonic current source I_h. Fig. 4 depicts the equivalent circuit of the power system at 60 Hz. It is noted that the inductive impedance of the four filters is expressed as (X_{ch}/n_h^2) where $h =$ 5, 7, 11, and 13, so the added filters can limit their corresponding hth harmonic distortion.

However, it is important to understand that the resonant point n_h must not be equal to the order h of the harmonic distortion (i.e., $n_h \neq h$). This is to avoid the filters being burned out due to series resonance. For example, the design resonant point n_h of the filter responsible for limiting 5th harmonic distortion should be a real number near the integer 5, but not the exact integer 5. Therefore, when we limit the hth order harmonic distortion, the equivalent circuit shown in Fig. 4 is rearranged by multiplying the inductive impedance by a factor h and by dividing the capacitance by a factor h. Fig. 5 shows the resultant equivalent circuit that is valid for any hth-order harmonic distortion. Two observations from Fig. 5 are stated in the following.

- When Q_{Fh} is fixed, the filter impedance Z increases as n_h decreases.
- When n_h is fixed, the filter impedance Z increases as Q_{Fh} decreases.

The harmonic distortion D_h at the PCC should meet the IEEE-519 standards. Assuming the bus voltage is V_{BUS}, we derive the expression for the harmonic distortion in the following:

$$I_{Sh} = \frac{V_{\text{BUS}}}{Z_{Sh} + Z_{th}} (\text{PU}) \tag{9}$$

$$I_{Mh} = \frac{V_{\text{BUS}}}{Z_{Mh}} (\text{PU}) \tag{10}$$

$$I_{Fih} = \frac{V_{\text{BUS}}}{Z_{Fih}} (\text{PU})$$

$$i = 5, 7, 11, \text{ and } 13, \text{ and } h = 2, 3, \cdots, 50 \tag{11}$$

where

$$Z_{Sh} = j\left(\frac{h}{S}\right), \quad Z_{th} = j\left(\frac{h}{S_t}\right)$$

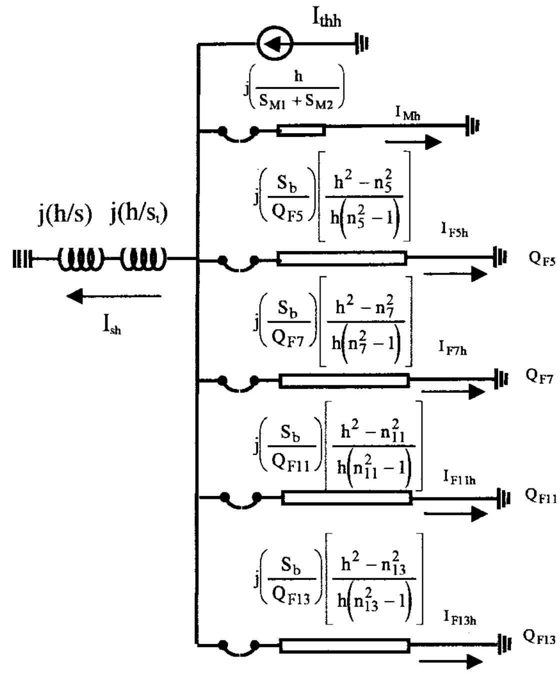

Fig. 5. The resultant equivalent circuit for any hth-order harmonic distortion where $h = 1, N$.

and

$$Z_{Mh} = j\left(\frac{h}{S_{M1} + S_{M2}}\right).$$

We also know

$$I_{thh} = I_{Sh} + I_{Mh} + I_{F5h} + I_{F7h} + I_{F11h} + I_{F13h} \tag{12}$$

where I_{thh} is the hth harmonic current from the harmonic current source in the model circuit. I_h is the actual harmonic current obtained from the manufacturer. Therefore, the actual harmonic current at the PCC has to be scaled based on the following equation:

$$I'_{Sh} = I_{Sh} \times \left(\frac{I_h}{I_{thh}}\right). \tag{13}$$

The hth harmonic distortion can then be expressed by the following equation:

$$D_h = \frac{I'_{Sh}}{I_{L1}} \times 100\% \tag{14}$$

where I_{L1} is the PU value of the rated current at PCC. Equation (14) can be simplified by neglecting the I_{Mh} without loss of generality, and by employing (1)–(13), which gives the expression for D_h shown in (15), at the bottom of the next page.

Equation (15) can further be expressed in a more generalized form that is valid for any number of filters by the following

TABLE I
IEEE-519 STANDARDS FOR MAXIMUM HARMONIC CURRENT DISTORTIONS

	MAXIMUM HARMONIC CURRENT DISTORTION (%)					
	HARMONIC ORDER (ODD HARMONICS)					
I_{SC}/I_L	h<11	11 ≤ h<17	17 ≤ h<23	23 ≤ h<35	h ≥ 35	THD_i %
<20	4.0	2.0	1.5	0.0	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

equation:

$$D_h = \frac{\left(\frac{1}{X_{Sh}+X_{th}}\right)\left(\frac{I_h}{I_{L1}}\right)}{\left(\frac{1}{X_{Sh}+X_{th}}\right)+\left(\frac{h^2}{S_b}\right)\left[-\Delta Q_c+(h^2-1)\sum_{i=m1}^{mf}\frac{Q_{Fi}}{h^2-n_i^2}\right]}. \tag{16}$$

The total harmonic distortion THD_i can then be expressed in terms of the individual harmonic distortion of D_h as follows:

$$\mathrm{THD}_i = \sqrt{\sum_{h=2}^{50} D_h^2}. \tag{17}$$

The objective here is to minimize the THD_i which is subject to the constraints discussed in the following section.

B. System Constraints

The system equations derived above are subject to several constraints, such as the following:

- reactive compensation;
- IEEE standards for maximum harmonic distortions;
- power source variations;
- filter detuning.

These factors serve as the boundary conditions of the system equations. The power system in Fig. 3 is used as an example to demonstrate how these constraints are evaluated in the computer program.

1) Reactive Compensation: The summation of the filter's reactive power has to be equal to the reactive power compensation as expressed in the following:

$$Q_{F5}+Q_{F7}+Q_{F11}+Q_{F13} = \Delta Q_c. \tag{18}$$

2) IEEE Standards for Maximum Harmonic Current Distortion: The harmonic distortion D_h has to meet the IEEE-519 standards [4] contained in Table I.

If $I_{SC}/I_L < 20$, Table I gives the upper bound of the 5th, 7th, 11th, and 13th harmonic current distortions in the following:

$$0 < D_5 < 4\% \tag{19}$$

$$0 < D_7 < 4\% \tag{20}$$

$$0 < D_{11} < 2\% \tag{21}$$

$$0 < D_{13} < 2\%. \tag{22}$$

3) System Variations: The power supplied by the Taiwan Electric Power Company has an approximately ±5% variation in voltage. This means that the SCC value does not remain constant, but rather varies between the lower and upper limits $\mathrm{SCC}_{\min}$ and $\mathrm{SCC}_{\max}$, respectively. Another uncertainty is that the frequency of the power supply contains ±1% variation, as expressed in the following:

$$\left|\frac{\Delta f}{f}\right| \le 1\%. \tag{23}$$

4) Filter Detuning: Filter detuning can result in the series resonance between the designed resonant point n_h and the hth harmonic. There are two major factors that contribute to the filter detuning, namely, temperature variation and manufacturing tolerance. The capacitance, for example, can have ±2% variation from its designed value due to season changes (i.e., summer versus winter). It can also have −5% to +10% variation due to the manufacturing. Therefore, the resultant variation in capacitance is defined by the following equation:

$$-7\% \le \frac{\Delta C}{C} \le 12\%. \tag{24}$$

Since most of the reactors use an air core, its inductance is not affected by temperature variations, but it is still subject to variation due to manufacturing tolerances. In general, there is an approximate ±3% variation from its designed value, which is expressed in the following:

$$-3\% \le \frac{\Delta L}{L} \le 3\%. \tag{25}$$

$$D_h = \frac{\left(\frac{I_h}{I_{L1}}\right)/(X_{sh}+X_{th})}{\left(\frac{1}{X_{Sh}+X_{th}}\right)+\left(\frac{h^2}{S_b}\right)\left[-\Delta Q_c+(h^2-1)\left(\frac{Q_{F5}}{h^2-n_5^2}+\frac{Q_{F7}}{h^2-n_7^2}+\frac{Q_{F11}}{h^2-n_{11}^2}+\frac{Q_{F13}}{h^2-n_{13}^2}\right)\right]} \tag{15}$$

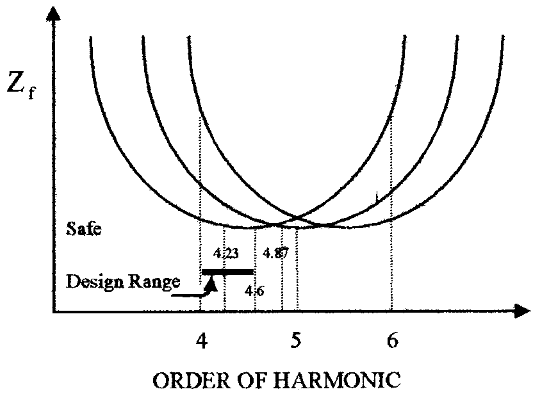

Fig. 6. Determination of safe range for designed resonant point.

5) Safe Design Range for Resonant Point: The designed resonant point for a single-tuned filter is determined by the following equation [5]:

$$n_h = \frac{1}{2\pi \cdot f\sqrt{LC}}. \tag{26}$$

Equation (26) states that the designed resonant point n_h is a function of frequency and filter inductance and capacitance. Any variation in these parameters can deviate the resonant point from its originally designed value. The resultant possible deviation from the designed value can be obtained by substituting (23)–(25) in (26), as in the following:

$$h \times \frac{1}{1.01 \times \sqrt{1.03 \times 1.12}} \leq n_h \leq h \times \frac{1}{0.99 \times \sqrt{0.97 \times 0.93}}$$

or

$$0.92h \leq n_h \leq 1.06h. \tag{27}$$

For example, if $h = 5$, (14) gives $4.60 \leq n_5 \leq 5.30$, and if $h = 4.6$, (14) gives $4.23 \leq n_{4.6} \leq 4.88$. This means that, to design a filter suppressing the 5th-order harmonic, and to preventing the filter from possible series resonance, the proper design range is 4.6, or less.

Fig. 6 depicts the idea of determining the safe range for the designed resonant point. For any hth harmonic, the safe range for determining the resonant point is defined in the following:

$$(h-1) < n_h \leq 0.92 \times h \tag{28}$$

where n_h is the designed resonant point, and h is the order of the harmonic to be suppressed by the designated filter. Based on the above discussion, the safe design ranges of the resonant points for the four designated filters for suppressing the 5th, 7th, 11th, and 13th filters are summarized in the following:

$$4 < n_5 \leq 5 \times 0.92 \tag{29}$$

$$6 < n_7 \leq 7 \times 0.92 \tag{30}$$

$$10 < n_{11} \leq 11 \times 0.92 \tag{31}$$

$$12 < n_{13} \leq 13 \times 0.92. \tag{32}$$

TABLE II
SOLUTION Q_{Fi} AND n_i

i-th ORDER HARMONIC	Q_{Fi}	n_i
5	2.37	4.60
7	1.69	6.44
11	3.20	10.12
13	2.74	11.96

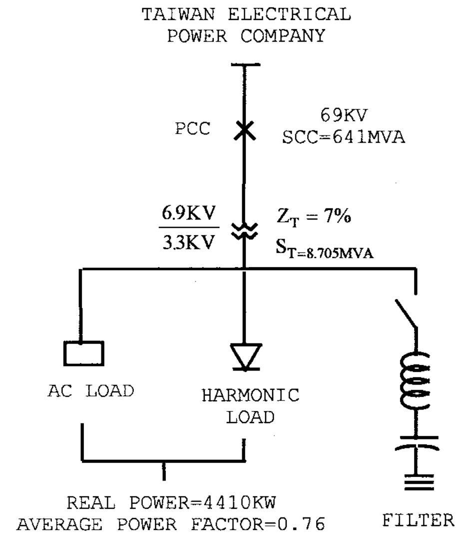

Fig. 7. One-line diagram of a small industrial plant.

TABLE III
SYSTEM INFORMATION OF THE PLANT

PARAMETER	VALUE
V_s	69.0 KV
S_b	10.0 MVA
SCC_{min}	641.0 MVA
S_t	8705.0 KVA
I_{SC}	5363.7 A
I_L	72.8 A
PORT AT BUS	3.3 KV
LOAD	5802 KVA

IV. MODEL IMPLEMENTATION

In Section III, we presented the mathematical formulations of the proposed power distribution model. This section explains the procedure and technique employed for obtaining the solutions. The program was written in Visual Basic and implemented on a PC-based computer.

A. Governing Equations

The system formulations and their constraints can be generalized for obtaining the solutions, namely, $Q_{Fm[i]}$ and $n_{m[i]}$ by minimizing the THD_i, which are described by the following

TABLE IV
HARMONIC CURRENTS I_h IN THE SYSTEM

ORDER	CURRENT (A)	ORDER	CURRENT (A)	ORDER	CURRENT (A)	ORDER	CURRENT (A)
1	1014.8	5	173.0	7	44.0	11	52.0
13	23.0	17	29.0	19	19.0	23	19.0
25	12.0	29	9.0	31	4.8	35	2.9
37	2.0	41	1.3	43	1.3	47	1.8
49	1.4						

TABLE V
PU TRANSFORMATIONS

SOURCE IMPEDANCE (Z_s) PU TRANSFORMATION

$$XZ_s = (1.0 \times \mathrm{PU}) \times \left(\frac{S_b}{SCC_s}\right) = (1.0 \times \mathrm{PU}) \times \left(\frac{10}{641}\right) = j0.015601\mathrm{PU}$$

TRANSFORMER IMPEDANCE (Z_t) PU TRANSFORMATION

$$XZ_t = (0.07 \times \mathrm{PU}) \times \left(\frac{S_b}{SCC_t}\right) = (0.07\mathrm{PU}) \times \left(\frac{10}{8.705}\right) = j0.080414\mathrm{PU}$$

BASE LOAD CURRENT PU TRANSFORMATION

$$I_L(\mathrm{PU}) = I_L / [10\mathrm{MVA}/(\sqrt{3} \times 69\mathrm{KV})] = 72.8 \times 0.011951\mathrm{PU} = 0.87\mathrm{PU}$$

HARMONIC CURRENT PU TRANSFORMATION

$$I_h(\mathrm{PU}) = I_h / [10\mathrm{MVA}/(\sqrt{3} \times 3.3\mathrm{KV})] = I_h \times 0.00057\mathrm{PU}$$

ORDER	CURRENT PU TRANS.	ORDER	CURRENT PU TRANS.	ORDER	CURRENT PU TRANS.	ORDER	CURRENT PU TRANS.
1	0.5800	5	0.0989	7	0.0251	11	0.0297
13	0.0131	17	0.0166	19	0.0109	23	0.0109
25	0.0069	29	0.0051	31	0.0027	35	0.0017
37	0.0011	41	0.0007	43	0.0007	47	0.0010
49	0.0008						

expression:

$$\min\{\mathrm{THD}_i\} = \min\{f(Q_{Fm[i]}, n_{m[i]})\} = \min\left\{\sqrt{\sum_{h=2}^{50} D_h^2}\right\} \tag{33}$$

subject to the constraints

$$\sum_{i=1}^{p} Q_{Fm[i]} = \Delta Q_c$$
$$\text{where } Q_{Fm[i]} > 0, \quad i = 1, 2, \cdots, p \text{ and } p \le 50 \tag{34}$$

$$0 < D_{m[j]} < M_{cr}\%, \quad j = 1, 2, \cdots, 50 \tag{35}$$

$$m[i] - 1 < n_{m[i]} \le m[i] \times 92\% \tag{36}$$

where

- $m[i]$ order of the harmonic to be suppressed;
- $n_{m[i]}$ designed resonant point of the filter suppressing the harmonic of order $m[i]$;
- $D_{m[j]}$ harmonic current distortion;
- $Q_{Fm[i]}$ reactive power of the filter suppressing the $m[i]$th-order harmonic;
- ΔQ_c reactive power compensation;
- M_{cr} IEEE-519 standards for maximum harmonic distortion $c = 1, \cdots, 5$ and $r = 1, \cdots, 5$.

B. Solution Procedure

To solve (33), both the Fermat Theorem and the SUMT [6] was employed.

By assuming $\Delta Q = 10$ Mvar, Table II contains the solutions of the system shown in Fig. 3 by using the developed computer program.

With known Q_{Fi} and n_i, the capacitance C and the inductance L can be calculated using (5)–(8) and (26). The harmonic current at each port of the filter limiting ith-order harmonic is calculated by the following equation:

$$I'_{Fih} = I_{Fih} \times \left(\frac{I_h}{I_{thh}}\right). \tag{37}$$

The reactor protective current is calculated using the following equation:

$$I_{Fi} = \sqrt{\sum_{h=1}^{50} I'^2_{Fih}} \times 130\%. \tag{38}$$

The capacitor protective voltage is calculated using the following equation:

$$V_{ci} = \sqrt{\sum_{h=1}^{50} \left(\frac{I'_{Fih} \times X_{ci}}{h}\right)^2} \times 110\%. \tag{39}$$

With all these design values calculated by the computer program, filters meeting all these specifications can then be ordered from the suppliers.

V. AN APPLICATION EXAMPLE

In this section, we employ the developed computer program to resolve the harmonic problems of a small industrial plant. Fig. 7 depicts the one-line diagram of the plant. The plant has an ac load and a harmonic load, and one of the objectives is to improve the power factor from 0.76 to 0.98. To determine the appropriate filters for the system, we follow the approach outlined in Fig. 2. First, we analyze the system before any filter is added to it.

A. System Analysis Before Filters Are Installed

Table III contains the information of the power system shown in Fig. 7. From this table, we get $I_{SC}/I_L = 73.68$. The ratio determines the maximum allowable harmonic current distortions from Table I. The plant engineers also provided a list of the harmonic currents in the system. This information is contained in Table IV.

TABLE VI
PCC INDIVIDUAL AND TOTAL DISTORTIONS OF HARMONIC CURRENTS

ORDER	D_h(%)	ORDER	D_h(%)	ORDER	D_h(%)	ORDER	D_h(%)
2	0.000	3	0.000	4	0.000	5	11.361
6	0.000	7	2.883	8	0.000	9	0.000
10	0.000	11	3.412	12	0.000	13	1.505
14	0.000	15	0.000	16	0.000	17	1.907
18	0.000	19	1.252	20	0.000	21	0.000
22	0.000	23	1.252	24	0.000	25	0.793
26	0.000	27	0.000	28	0.000	29	0.586
30	0.000	31	0.310	32	0.000	33	0.000
34	0.000	35	0.195	36	0.000	37	0.126
38	0.000	39	0.000	40	0.000	41	0.080
42	0.000	43	0.080	44	0.000	45	0.000
46	0.000	47	0.115	48	0.000	49	0.090

$$THD_i = \sqrt{\sum_{2}^{49} D_h^2} = 12.619\%$$

To solve for (Q_{F5}, n_5) and (Q_{F7}, n_7) by minimizing THD_i:

$$\min(THD_i)$$

subject to:

$0 < D_5 < 5\%$;

$0 < D_{11} < 2.25\%$;

$0 < D_{23} < 0.75\%$;

$0 < D_{25} < 0.75\%$;

$Q_{F5} + Q_{F7} = 2.875$

$Q_{F5} > 0$; and

$Q_{F7} > 0$.

where

$$D_h = \frac{\left(\frac{1}{0.0156h + 0.0804h}\right) \times \left(\frac{I_h}{72.8}\right)}{\left(\frac{1}{0.0156h + 0.0804h}\right) + \frac{h^2}{10}\left[-2.875 + (h^2 - 1)\left(\frac{Q_{F5}}{h^2 - n_5^2} + \frac{Q_{F7}}{h^2 - n_7^2}\right)\right]}$$

Fig. 8. System equations and constraints.

B. Inclusion of Necessary Filters

From the system analysis before filters are installed, it is obvious that the 5th, 11th, 23rd, and 25th orders of harmonic currents are over the maximum allowable limits. These four harmonic currents are indicated in Table V. We first include two single-tuned filters for suppressing the 5th- and 7th-order harmonics.

Based on the information provided in Tables III and IV, the PU transformation was performed and summarized in Table V.

The calculated harmonic current distortions by the computer program are summarized in Table VI.

It is noted here that the filter suppressing lower order harmonic should be installed earlier. This is to avoid the possible parallel resonance between the lower harmonic and the filter designated for suppressing the higher order harmonic.

C. System Formulations and Constraints

The system formulations and constraints are depicted in Fig. 8.

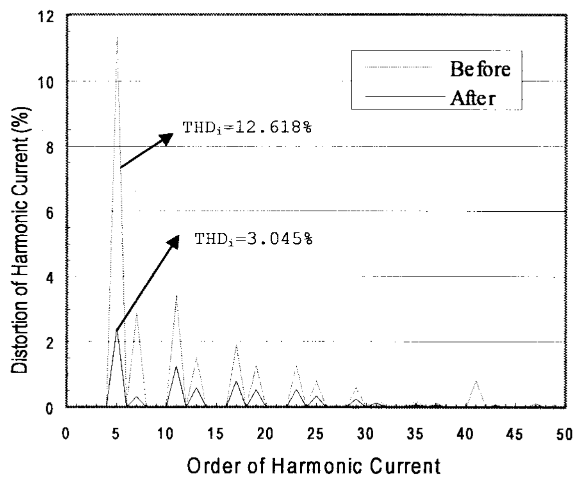

Fig. 9. Comparison of harmonic currents before and after the two filters suppressing the 5th and the 7th harmonics are installed.

D. Obtaining Solutions Using the SUMT

The solutions Q_{Fi} and n_i ($i = 5$ and 7) were obtained using the SUMT implemented in the program. Table VII contains the results calculated by the program. It is noted that it took 17.6 s to arrive at the converged solutions.

E. System Analysis After Filters Are Installed

From the solutions Q_{Fi} and n_i ($i = 5$ and 7) obtained above, the distortions of harmonic currents and voltages at PCC can then be evaluated using (16). Figs. 9 and 10 compare the improvements before and after the two filters are installed. From the comparison, it is seen that all harmonics were greatly improved after adding the two filters. It is also noted that no parallel resonance was observed after the two filters were installed in the system.

From the results, it is obvious that the developed power distribution model is very capable of limiting harmonics and improving reactive compensation. Also, the implemented computer program shows very quick turnaround in obtaining the solutions.

F. Recommendations of Filters With Proper Specifications

Up to this point, the proper design values of the two added filters are well defined. The protective current and voltage of

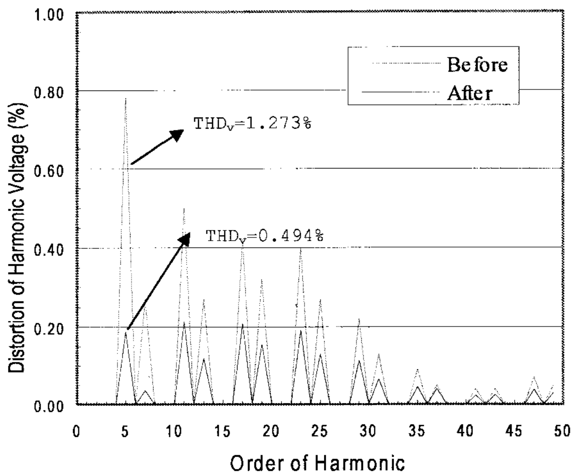

Fig. 10. Comparison of harmonic voltages before and after the two filters suppressing the 5th and the 7th harmonics are installed.

TABLE VII
SOLUTIONS COMPUTED BY THE PROGRAM

FILTER	F(#5)	F(#7)
n_i	4.60	6.44
Q_{Fi} (KVAR)	1615	1260
C (uf)	375	300
L (mh)	0.887	0.566
SOLUTION TIME: 17.6 SECONDS		

TABLE VIII
RECOMMENDED PROTECTIVE CURRENT AND VOLTAGE

FILTERS	F(#5)	F(#7)
Protective Current (AMP)	325.9	231.5
Protective Voltage (KV)	3.98	3.96

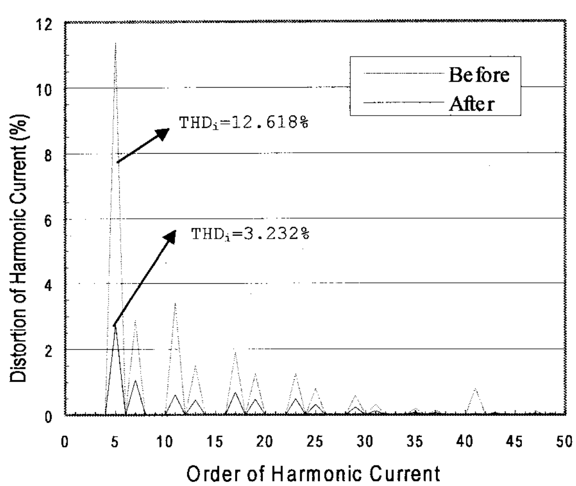

Fig. 11. Comparison of harmonic currents before and after the three filters suppressing the 5th, 7th, and 11th harmonics are installed.

the two filters are evaluated from the calculated C and L values contained in Table VII.

G. Situations When More Than Two Filters Are Added in the System

Although only two filters were needed to satisfy all the system requirements, it is interesting to study the situations

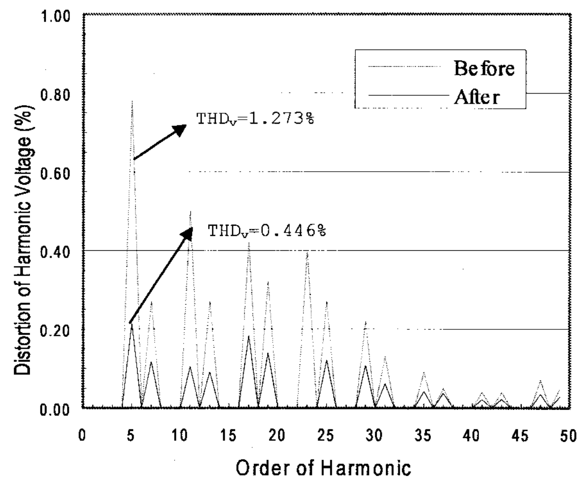

Fig. 12. Comparison of harmonic voltages before and after the three filters suppressing the 5th, 7th, and 11th harmonics are installed.

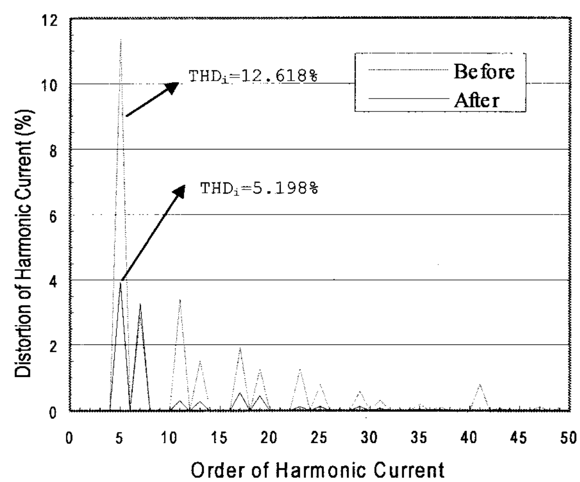

Fig. 13. Comparison of harmonic currents before and after the four filters suppressing the 5th, 7th, 11th, and 25th harmonics are installed.

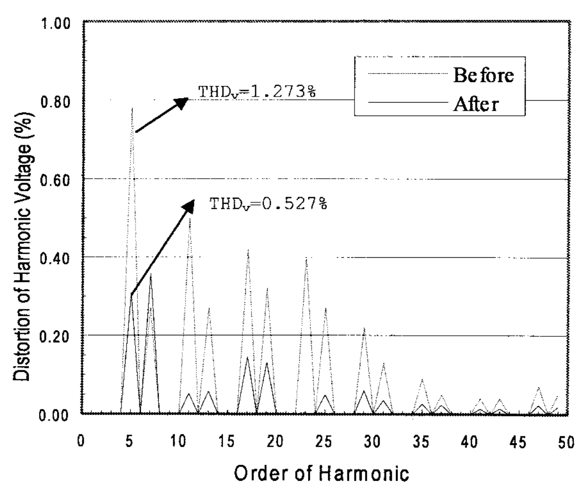

Fig. 14. Comparison of harmonic voltages before and after the four filters suppressing the 5th, 7th, 11th, and 25th harmonics are installed.

when more than two filters are installed in the system. A simulation was performed to examine the situation when three filters suppressing the 5th, 7th, and 11th harmonics were

TABLE IX
SOLUTIONS COMPUTED BY THE PROGRAM

FILTER	F(#5)	F(#7)	F(#11)
n_i	4.60	6.44	10.12
Q_{Fi} (KVAR)	2099	343	433
C (uf)	487	82	106
L (mh)	0.684	2.071	.649
SOLUTION TIME: 6.2 SECONDS			

TABLE X
SOLUTIONS COMPUTED BY THE PROGRAM

FILTER	F(#5)	F(#7)	F(#11)	F(#25)
n_i	4.60	6.44	10.12	23
Q_{Fi} (KVAR)	1453	158	1198	66
C (uf)	337	37.5	289	16
L (mh)	0.986	4.524	0.238	.829
SOLUTION TIME: 3 MINUTES AND 5.3 SECONDS				

included in the system. Table IX summarizes the results of the simulations. Figs. 11 and 12 show the improvements before and after three filters suppressing the 5th-, 7th-, and 11th-order harmonic distortions.

We further look at the situation when four filters suppressing the 5th, 7th, 11th, and 25th harmonics. Table X summarizes the results from the simulation. Figs. 13 and 14 show the improvements before and after three filters suppressing the 5th-, 7th-, 11th-, and 25th-order harmonic distortions. The results demonstrate the fact that installing more filters in the system does not necessarily mean better improvement of harmonic distortions.

VI. CONCLUSION

In conclusion, the proposed power distribution model was successfully implemented as a PC-based computer program. A user-friendly GUI was also integrated with the analysis module for design engineers.

A small industrial plant was selected to demonstrate the developed power distribution model in limiting harmonics and improving reactive compensation. Results from the simulations show that the developed computer program can reduce costs and design cycle time for designs of real-world industrial power distribution systems.

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